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Load-sharing characteristics of planetary gear transmission in horizontal axis wind turbines

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ABSTRACT

With the increase of wind turbine size, gravity becomes an important non-torque excitation source. Gravity disrupts the cyclic symmetry of the planetary gear and causes unequal load-sharing. Because of the specific operation conditions, the bedplate will tilt and lead to the offset of the gear plane and vertical plane. Taking gravity, tooth separation, backside contact and bedplate tilt angle into consideration, a rotational-translational-axial dynamic model of the spur planetary gear is developed. With two different load-sharing factor models, the load-sharing characteristics of the planetary gear in horizontal axis wind turbines are numerically investigated. The effects of gravity, ring support stiffness and bedplate tilt angle on load-sharing characteristics are systematically examined. When planets move to certain positions, severe unequal load-sharing and backside contact are more likely to happen. Load-sharing characteristics change with the bedplate tilt angle and the ring support stiffness, and the variation trend is closely related to the occurrence of tooth separation and backside contact.

1. Introduction

In planetary gear transmissions, multiple planet gears are used to form the power split, which allows the load to be shared by the planets. This makes planetary gears with compact structure and large torque-to-weight ratio. Planetary gear is widely used in modern wind turbines and has become one of the focuses in wind turbine researches [1–4]. In horizontal axis wind turbines, planetary gears with three equally spaced planets are widely used. In the ideal situation, the planetary gear can achieve good load-sharing effect [5]. But in practice, because of the influence of the flexible support and manufacturing and assembly errors, unequal load-sharing phenomenon is remarkable and leads to failures [6–9]. Therefore, it is an important issue to investigate the load-sharing characteristics of the planetary gear.

Load-sharing in planetary gear systems has been investigated extensively. Lu [10] analyzed the effects of manufacturing and installation errors on load-sharing characteristics using a linear dynamic model. Kahraman [6] established a nonlinear time-varying dynamic model, and quantitatively investigated the influence of the main design parameters, manufacturing and installation errors on load-sharing conditions. Bodas and Kahraman [7] investigated the influence of the manufacturing errors using an improved contact model. Considering the instantaneous geometric shapes influenced by tooth deformation and errors, Gu and Velex [8] illustrated the influence of planet position errors on the load-sharing characteristics. In the experimental aspect, Hidaka and Terauchi [9] investigated the unequal load-sharing caused by manufacturing and installation errors. Hayashi [11] measured the shear strain of planet pins to investigate the load-sharing characteristics. Kahraman [12] analyzed the effect of ring thickness through experimental and theoretical analysis. The research showed that the support way of the ring was one of the key factors in the design process. Singh [5] physically

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Nomenclature

N	Number of planets
I	Moment of inertia
m	Mass
r	Base radii
γ	Bedplate tilt angle
ψ_j	Circumferential angle of planets
α_s, α_r	Pressure angle
b_s, b_r	Backlash along the line of action
k_{su}, k_{ru}, k_{cu}	Torsional support stiffness
$k_{sj}^d,\ k_{rj}^d$	Drive-side mesh stiffness
$k_{sj}^b,\ k_{rj}^b$	Backside mesh stiffness
$\delta_{sj}^d,\ \delta_{rj}^d$	Drive-side mesh deflection
$\delta_{sj}^b,\ \delta_{rj}^b$	Backside mesh deflection
Ω_c	Carrier rotating frequency
u	Rotational displacement
$\xi_j, \eta_j, z_j, j = 1, 2, \ldots N$	Translations of the planets
$x_l, y_l, z_l, l = c, r, s$	Translations of the carrier, ring and sun
$f_{sj}^b,\ f_{rj}^b$	Gear mesh force of drive-side contact
$f_{sj}^d,\ f_{rj}^d$	Gear mesh force of drive-side contact
$f_c^u,\ f_s^u$	Torque load on the carrier and sun
$f_j^\xi,\ f_j^\eta,\ f_j^z,\ j = 1, 2, \ldots, N$	Gravity forces on planets
$f_l^x,\ f_l^y,\ f_l^z,\ l = c, r, s$	Gravity forces on the carrier, ring and sun
Δ_{cr}	Radial clearance of carrier-ring bearing
$k_v, k_{vz}, v = c, r, s, p$	Radial and axial bearing stiffness
k_{cr}, k_{ca}	Radial and axial stiffness of carrier-ring bearing
$f_{cr}^x,\ f_{cr}^y,\ f_{cr}^z$	Carrier-ring bearing forces

Subscript

c	Carrier
r	Ring
s	sun
p	planet

superscript

b	Backside contact
d	Drive-side contact

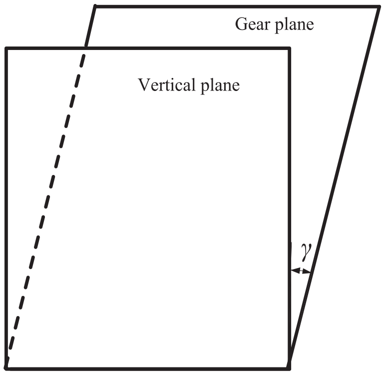

Fig. 1. Sketch map of the bedplate tilt angle.